Ground-based GNSS and satellite observations of severe ionospheric irregularities during space weather events

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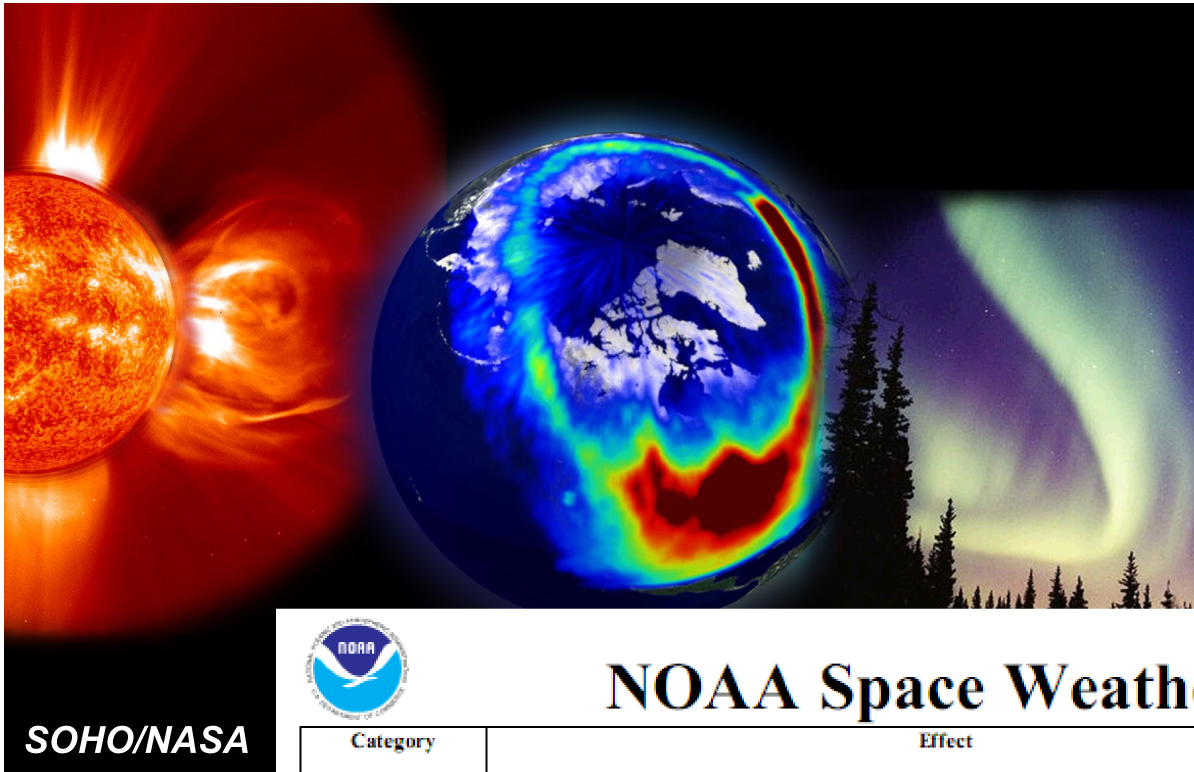
Ionospheric responses on Space Weather



Near Earth plasma environment 7is a final chain of space weather phenomena started from the Sun

As response to Space Weather ionosphere can experience depletions or enhancements in plasma density/total electron content, altitudinal and geographical redistribution of ionospheric plasma different from quite condition, formation of plasma irregularities and gradients

NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)

Ionospheric plasma irregularities detection using GNSS observations

The open questions:

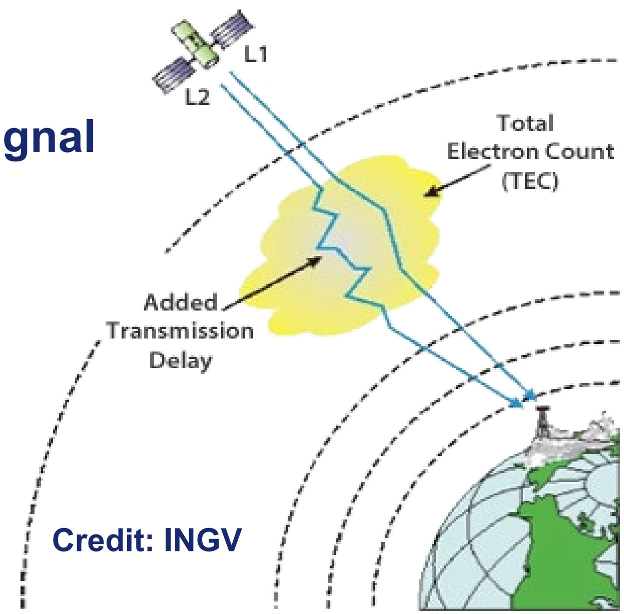
When and where ionospheric plasma irregularities are developed?

Our task:

Monitoring of the ionospheric irregularities using GNSS signals.

Our approach:

The TEC rapid changes analysis on the base of GNSS signal measurements

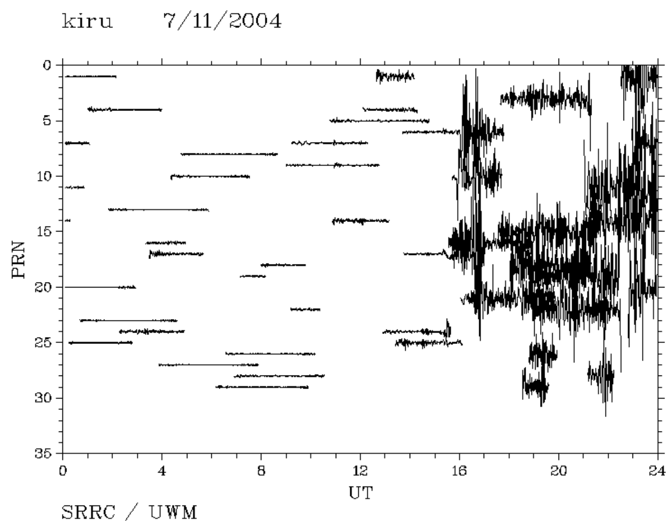


Credit: INGV

Methodology

Ionospheric irregularities can be characterized by its impact on amplitude and phase of the received GNSS signal.

ROT (Rate of TEC change, dTEC/dt) as a measure of phase fluctuation activity (*Pi et al, 1997*)



ROTI (Rate of TEC change Index, standard deviation of ROT) characterizes severity of the GNSS phase fluctuations. ROT/ROTI techniques was deweloper by NASA JPL team (Pi et al., 1997)

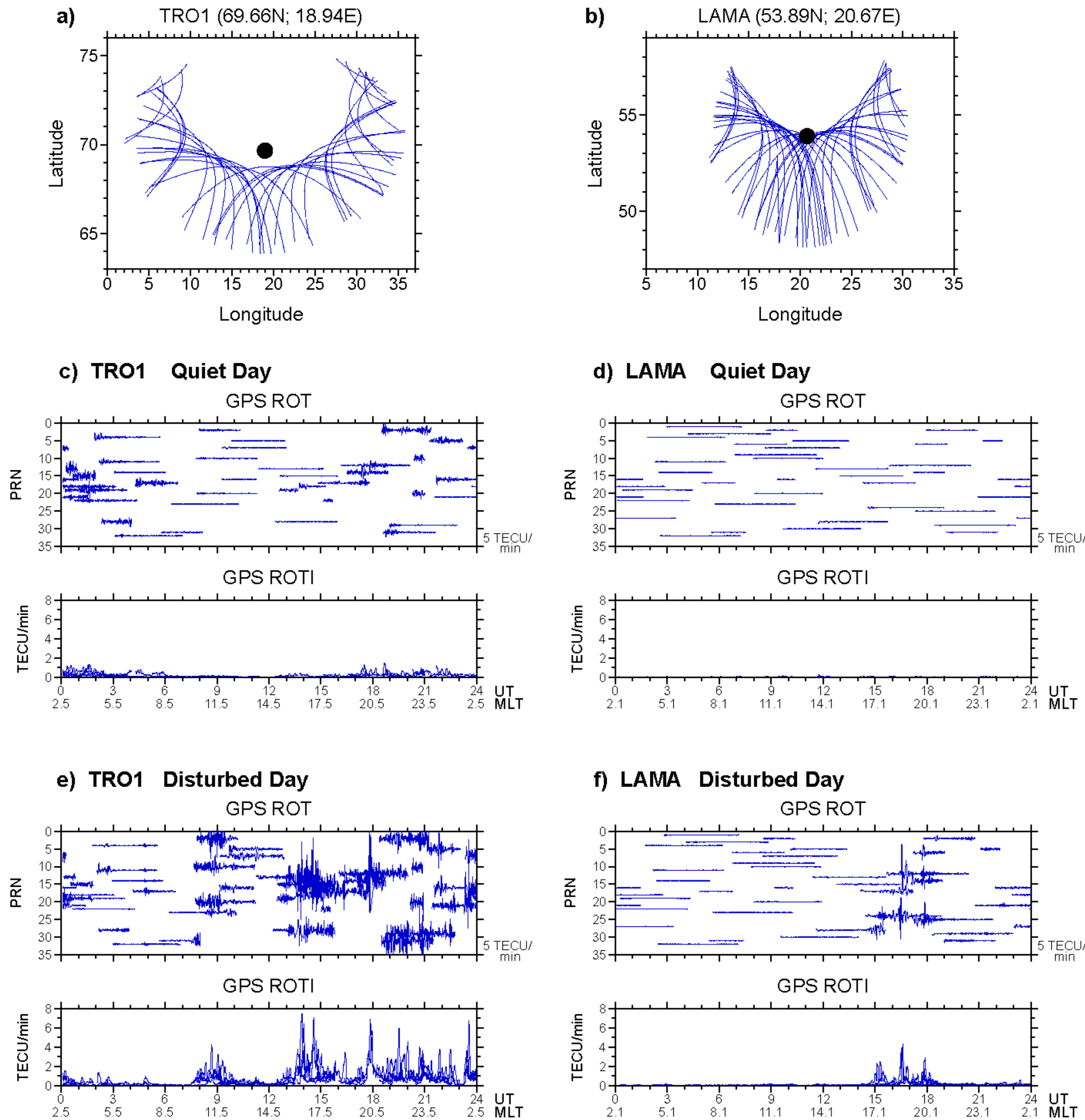
Basic approach:

1. **Rate of TEC (dTEC/dt) calculation**
2. **Rate of TEC Index (ROTI) estimation**

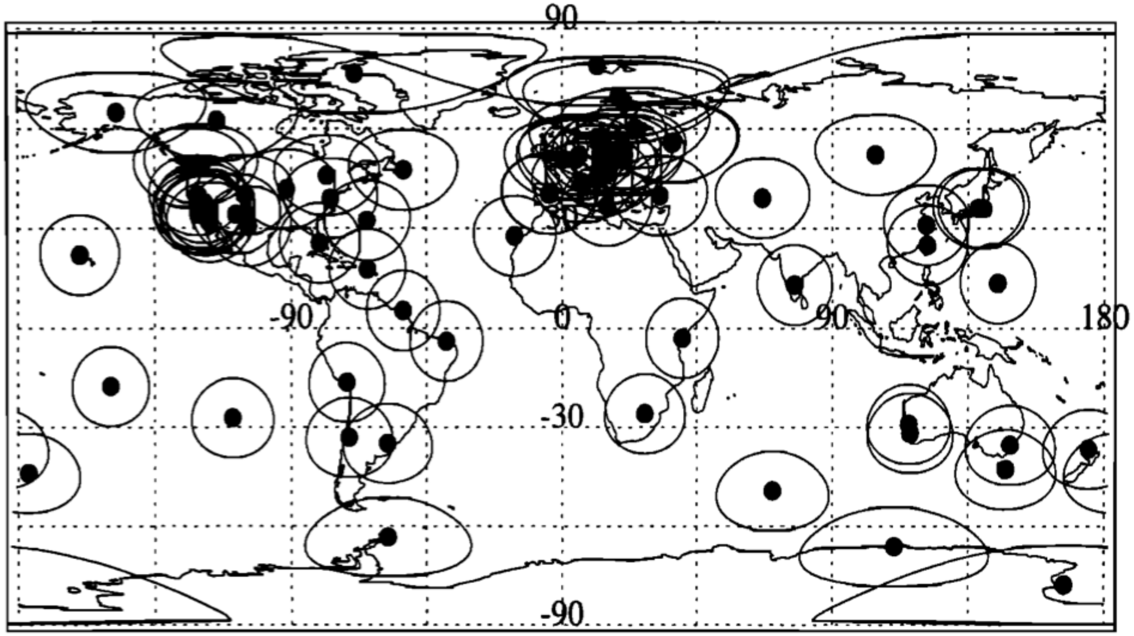
ROTI is calculated as tandard deviation of ROT on 5 min interwal for 30 second resolution GNSS measurements

Methodology

ROT and ROTI calculated for high-latitude (Tromso, left) and mid-latitude (Lama, right) stations



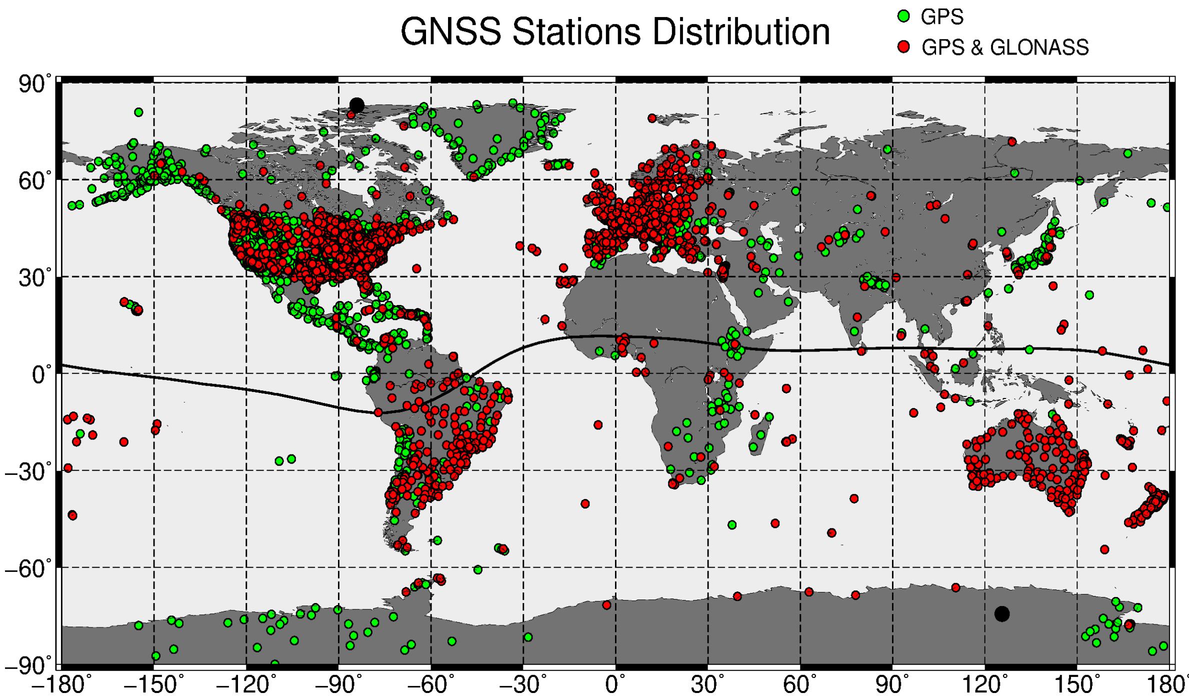
World distribution of GNSS tracking stations



Year 1996

More than 100 GPS stations

Courtesy Manucci et al, 1998



Year 2024

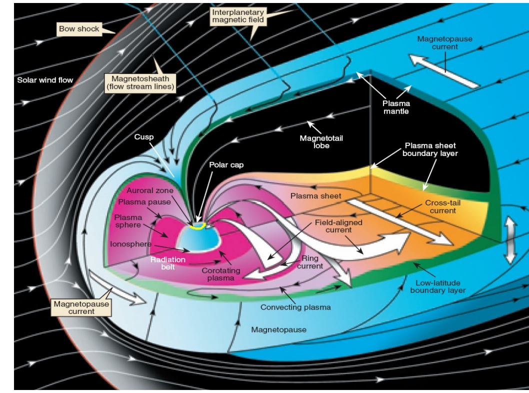
~ 6300 stations

~3500 multi-GNSS stations

(GPS + GLONASS)

Zakharenkova et al, JGR, 2016

IGS ROTI Maps



Basic approach:

The Rate of TEC Index mapping

Ionospheric plasma variability drivers:

- Solar radiation

- Geomagnetic field

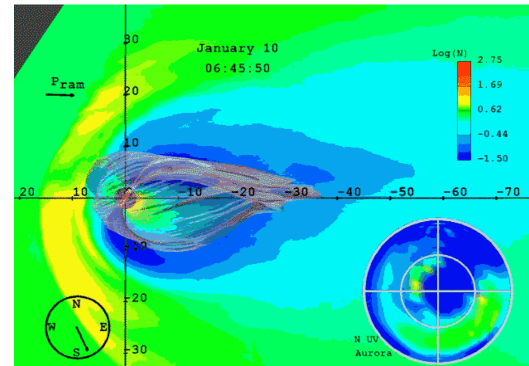
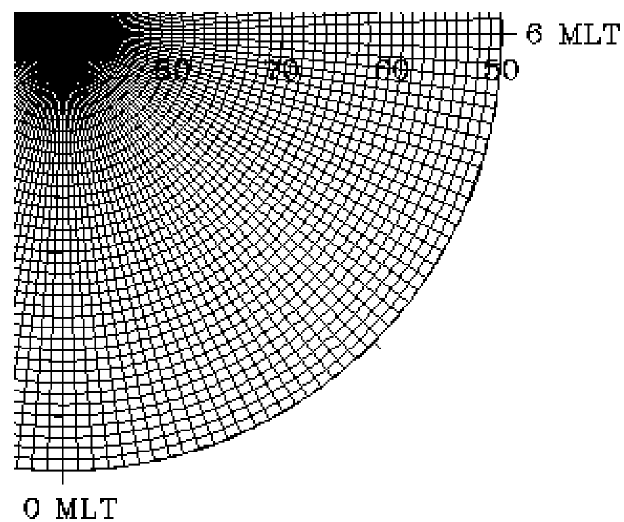


Image credit: SRI International

The coordinates system:

Magnetic Local Time (MLT) and

Corrected Magnetic Latitude (MLAT)



IGS INTERNATIONAL GNSS SERVICE

IGS – International GNSS Service

IGS provides, on an openly available basis, GNSS data, products and services in support of; positioning, navigation and timing

IGS ROTI Maps

ROTI maps are available for the period from 2010 to present on NASA CDDIS

- Developed in University of Warmia and Mazury IGS data analysis center
- Introduced on 2013, IGS GB meeting
- Pilot phase started on 2014 after IGS Workshop in Pasadena

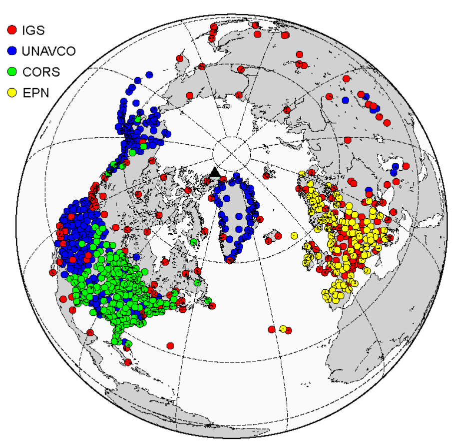
(Cherniak et al, 2014, Radio Science)

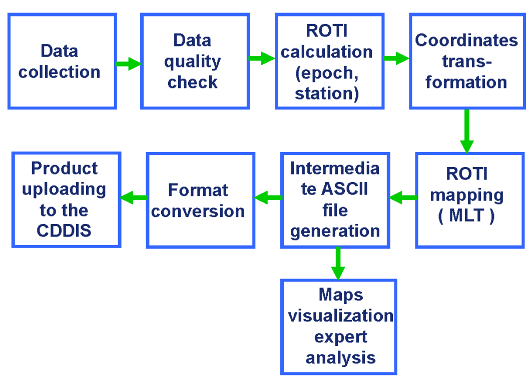
- Tested within framework of ESA Monitor-2 project on 2015-2016

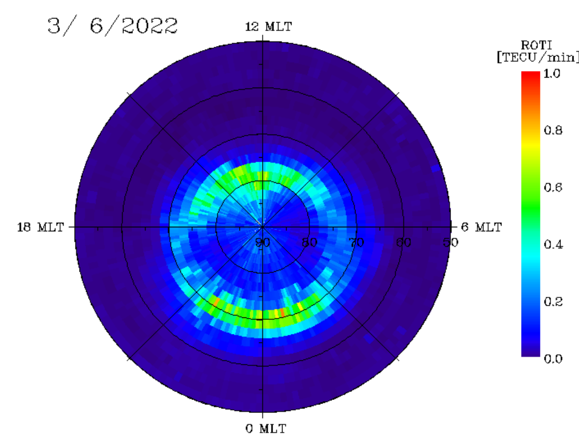
(Béniguel et al, 2017, Angeo)

- Accepted on 2017 as official IGS product for ionospheric irregularities specification

(Cherniak et al, 2018, GPS Solutions)

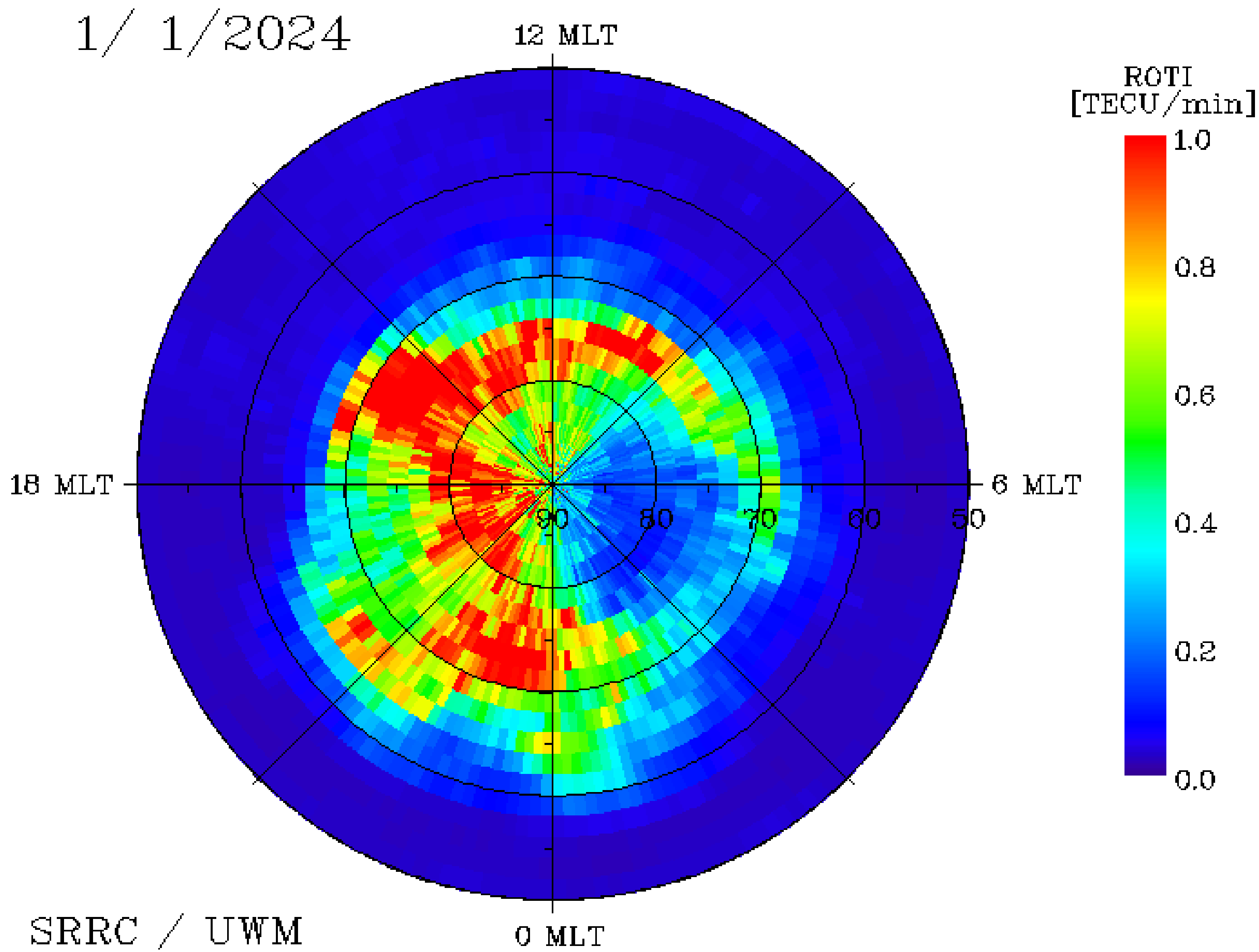






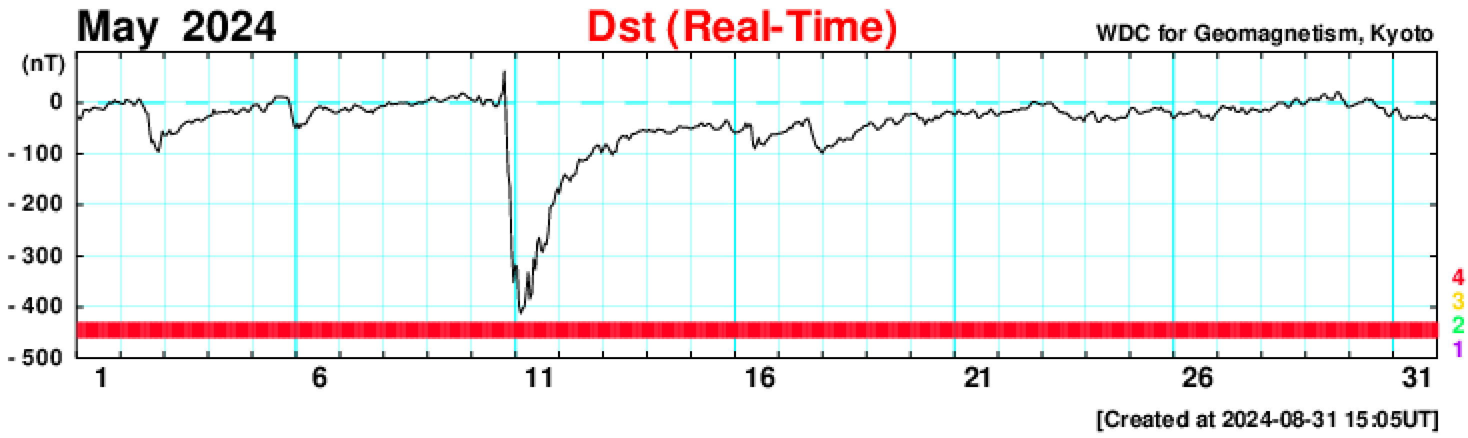
Detailed description of the ROTI Maps Product available in the paper Cherniak et al., GPS Solution, 2018.

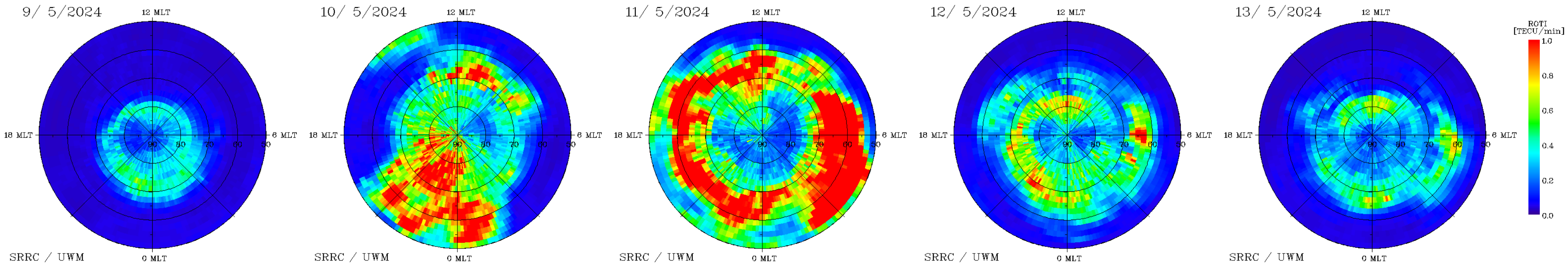
IGS ROTI Maps: day-to-day ionospheric irregularities variability.



IGS ROTI Maps: application

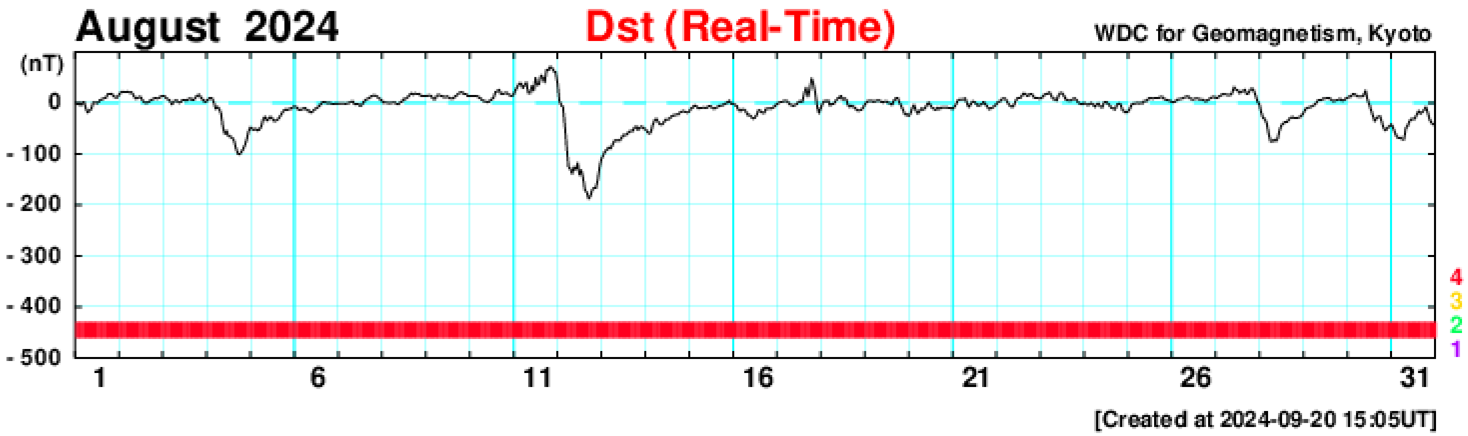
Ionospheric irregularities evolution during May 2024 superstorm

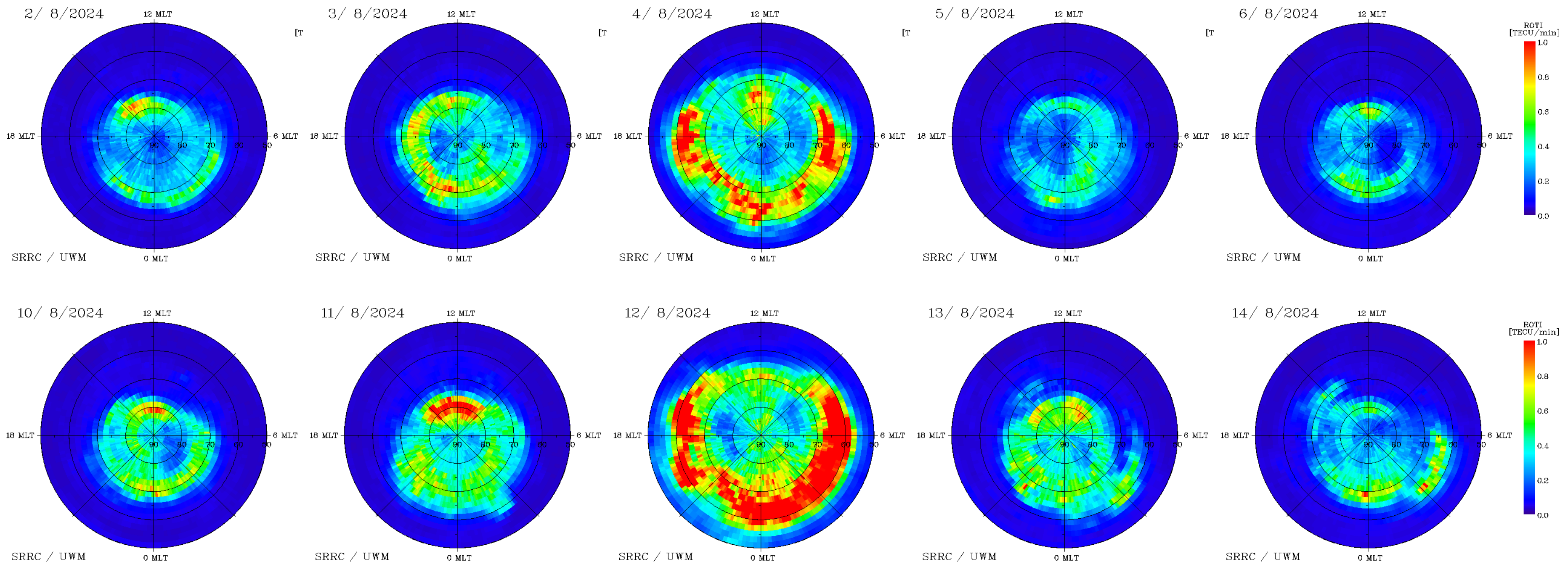




IGS ROTI Maps: application

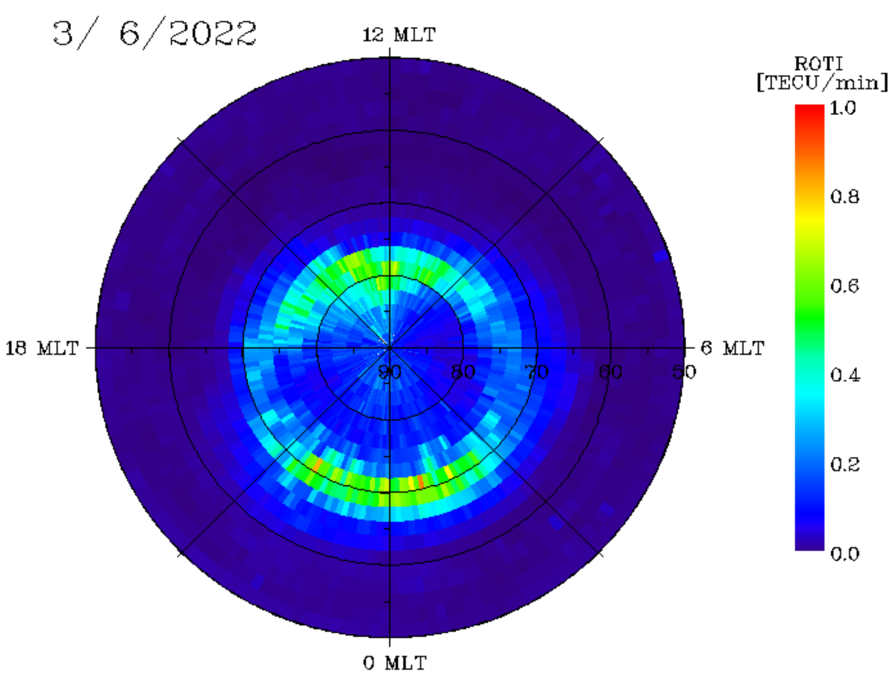
Ionospheric irregularities evolution during moderate and strong geomagnetic storms on August 2024



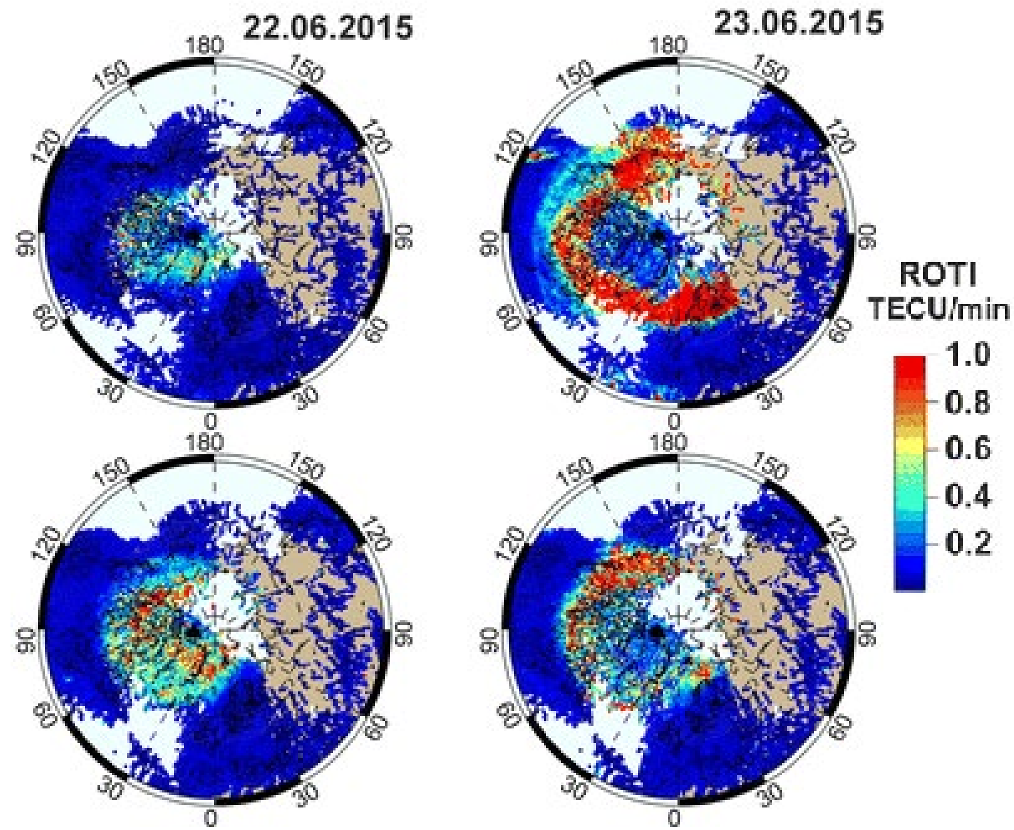


Daily IGS ROTI Maps vs high resolution global ROTI maps

Two level of ROTI mapping \for ionospheric irregularities detection and tracing



Cherniak et al, 2017



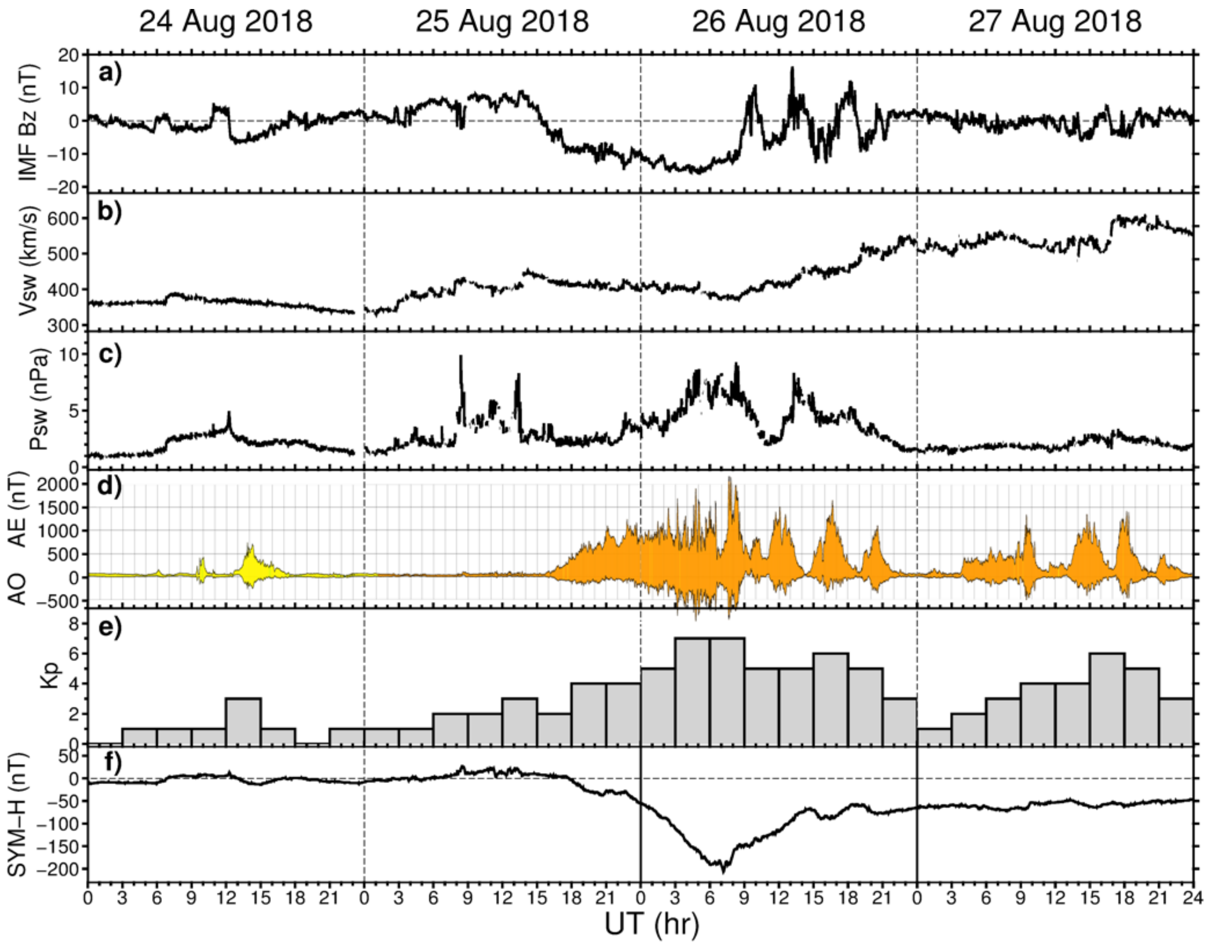
Cherniak et al, 2016

Daily MLAT-MLT IGS ROTI Maps for specification of large-scale pattern of irregularities occurrence (e.g. irregularities oval)

High resolution ROTI maps (up to 5 min resolution) – ionospheric irregularities dynamics in more detail

Dynamics of ionospheric irregularities traced using GNSS ROTI maps.

August 2018 geomagnetic storm.



Strong geomagnetic storm near solar minimum

Min SYM-H –175 nT

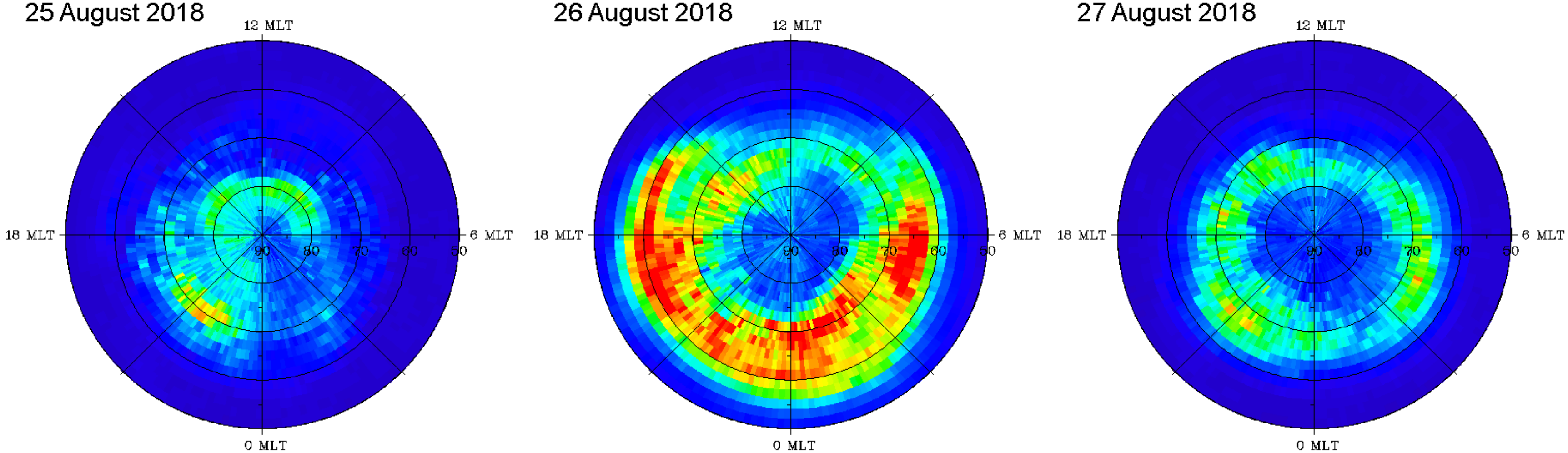
Dynamics of ionospheric irregularities traced using GNSS ROTI maps.

August 2018 geomagnetic storm.

25 August 2018

26 August 2018

27 August 2018

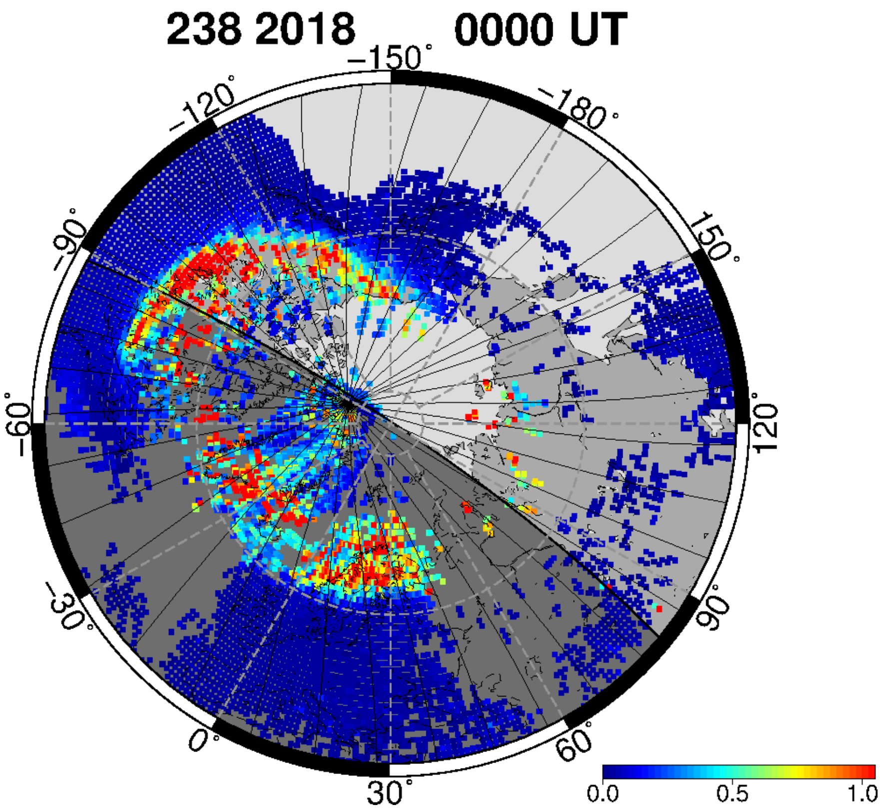


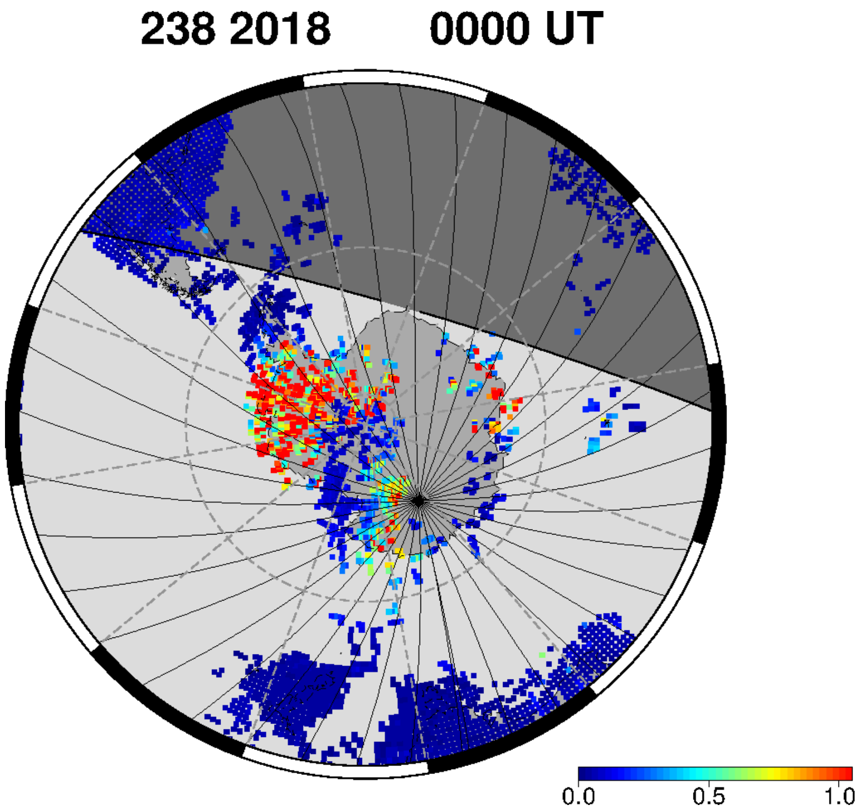
F10.7 - 68 SFU
Min SYM-H –175 nT

Daily MLT-MLAT ROTI maps for the Northern Hemisphere for 25–27 August 2018. and 15-18 March 2015

Dynamics of ionospheric irregularities traced using GNSS ROTI maps.

August 2018 geomagnetic storm.

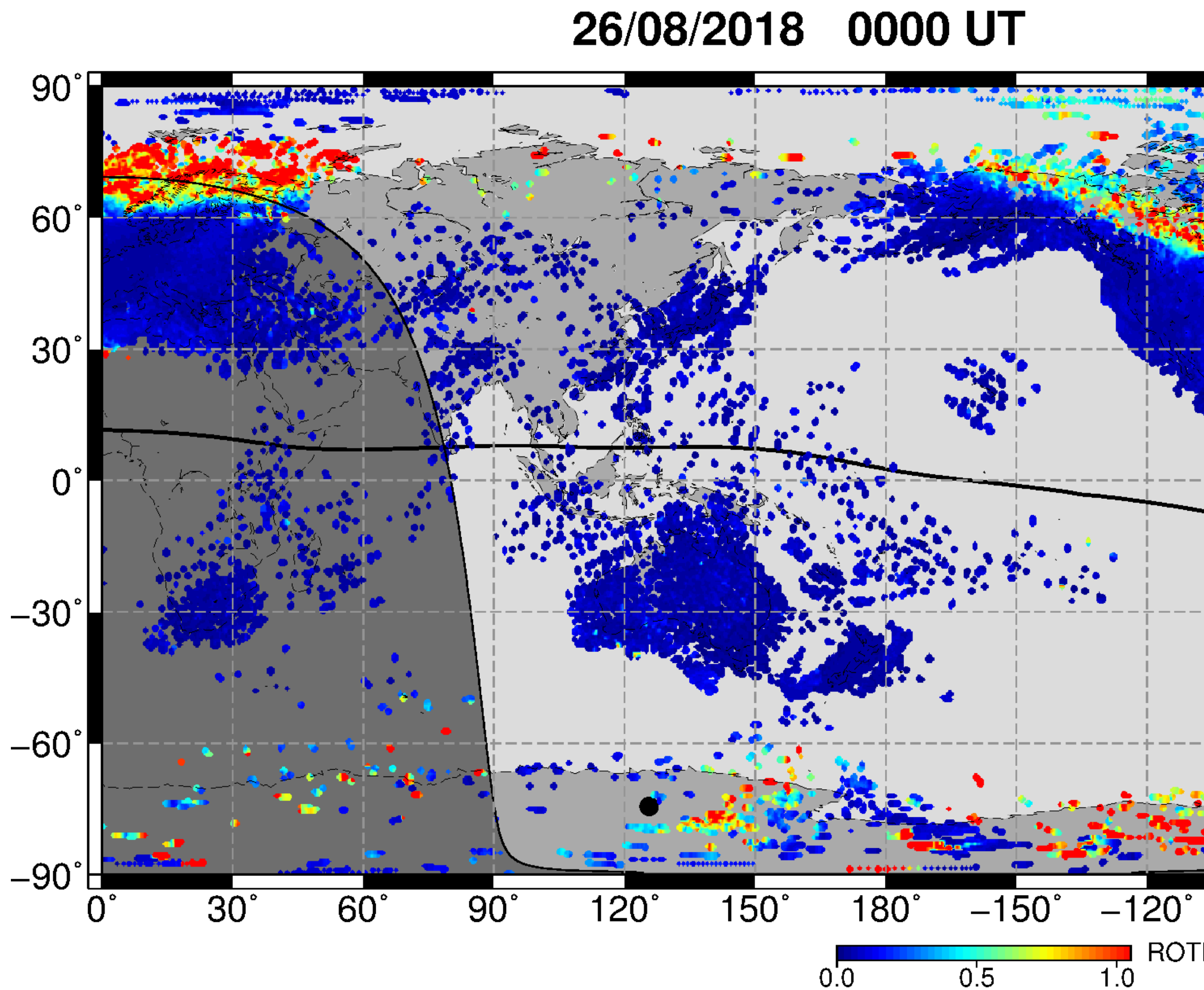




High/mid ionosphere response to August 2018 geomagnetic storm. Dynamics of ionospheric plasma irregularities distribution by high-resolution ROTI maps

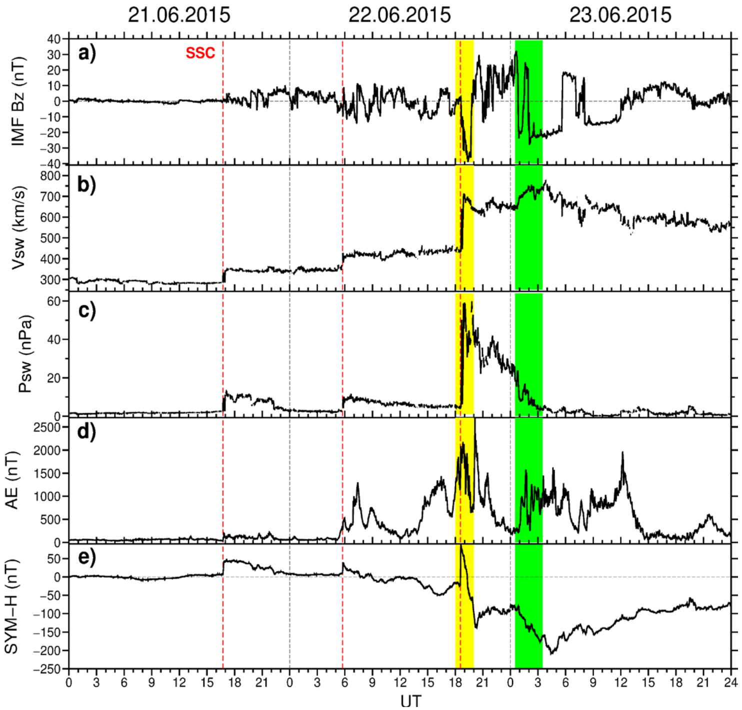
Dynamics of ionospheric irregularities traced using GNSS ROTI maps.

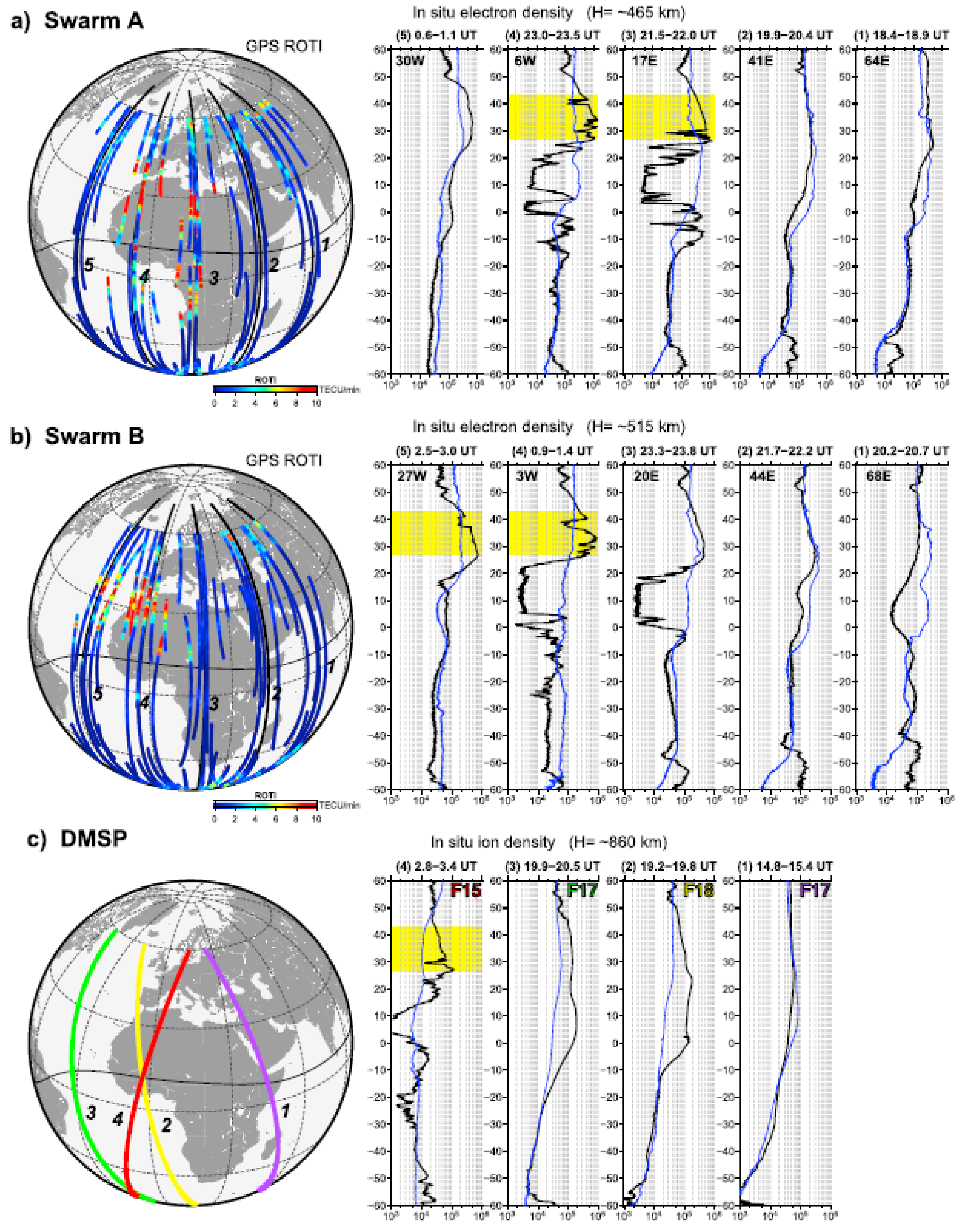
August 2018 geomagnetic storm.



Cherniak&Zakharenkova, JGR, 2022

The June 2015 geomagnetic storm
Plasma bubbles on midlatitudes





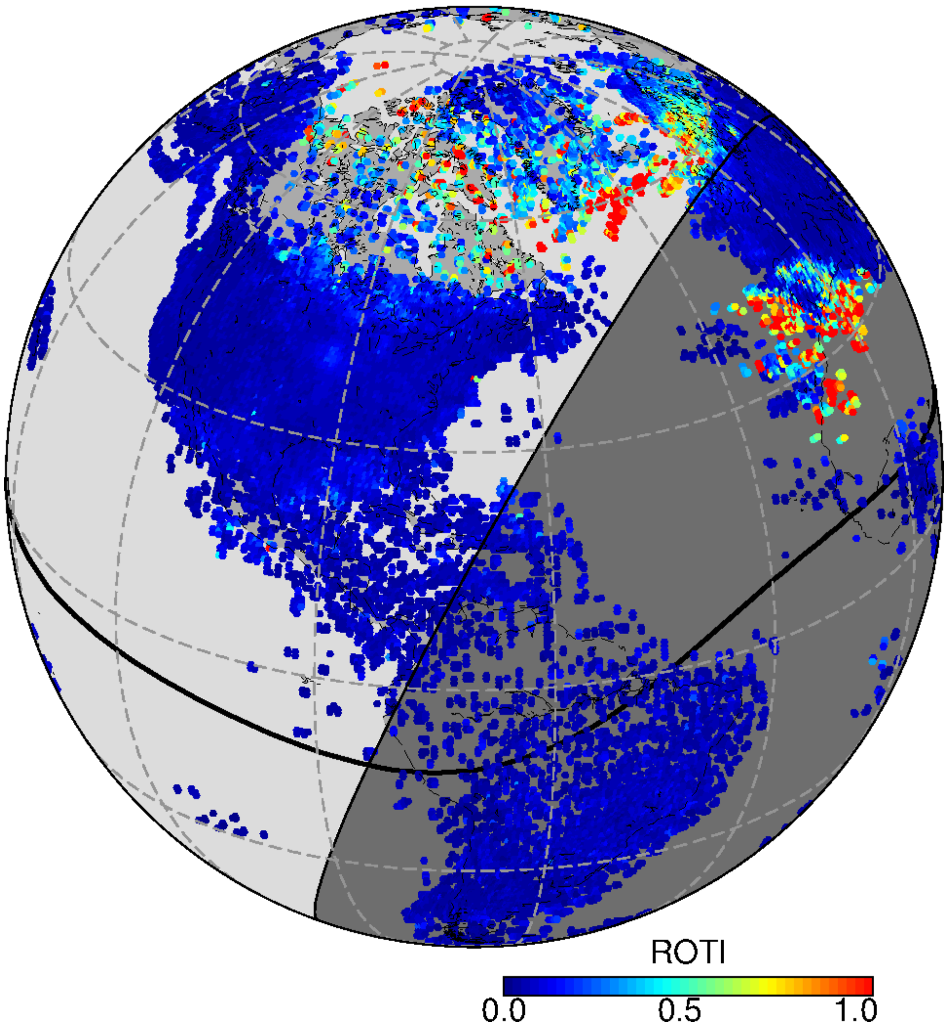
The plasma bubbles in signatures spaceborne GPS ROTI and Ne from Swarm satellites passes and DMSP in situ ion density.

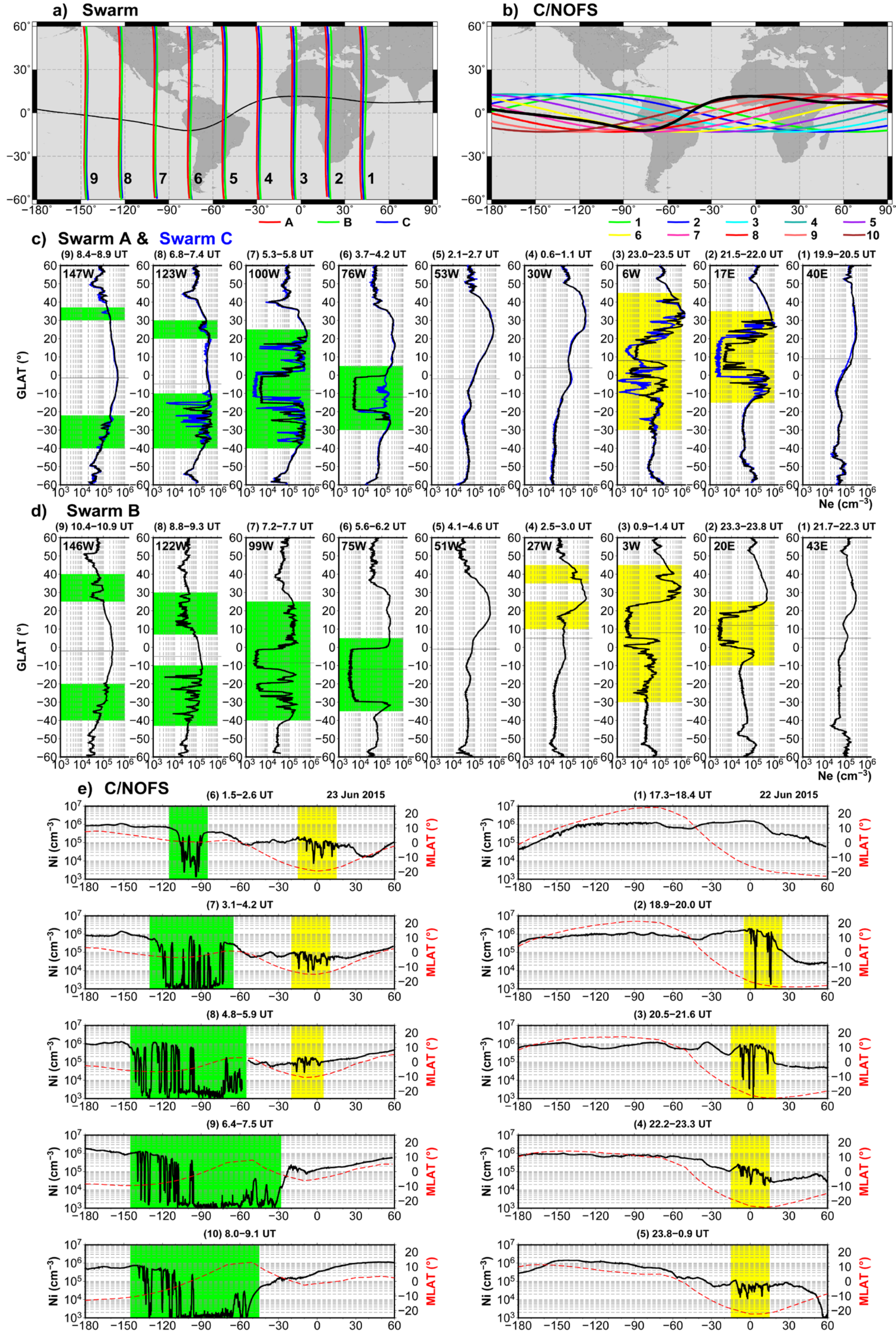
Cherniak&Zakharenkova, GRL, 2016

The June 2015 geomagnetic storm
Plasma bubbles on midlatitudes

Global overview

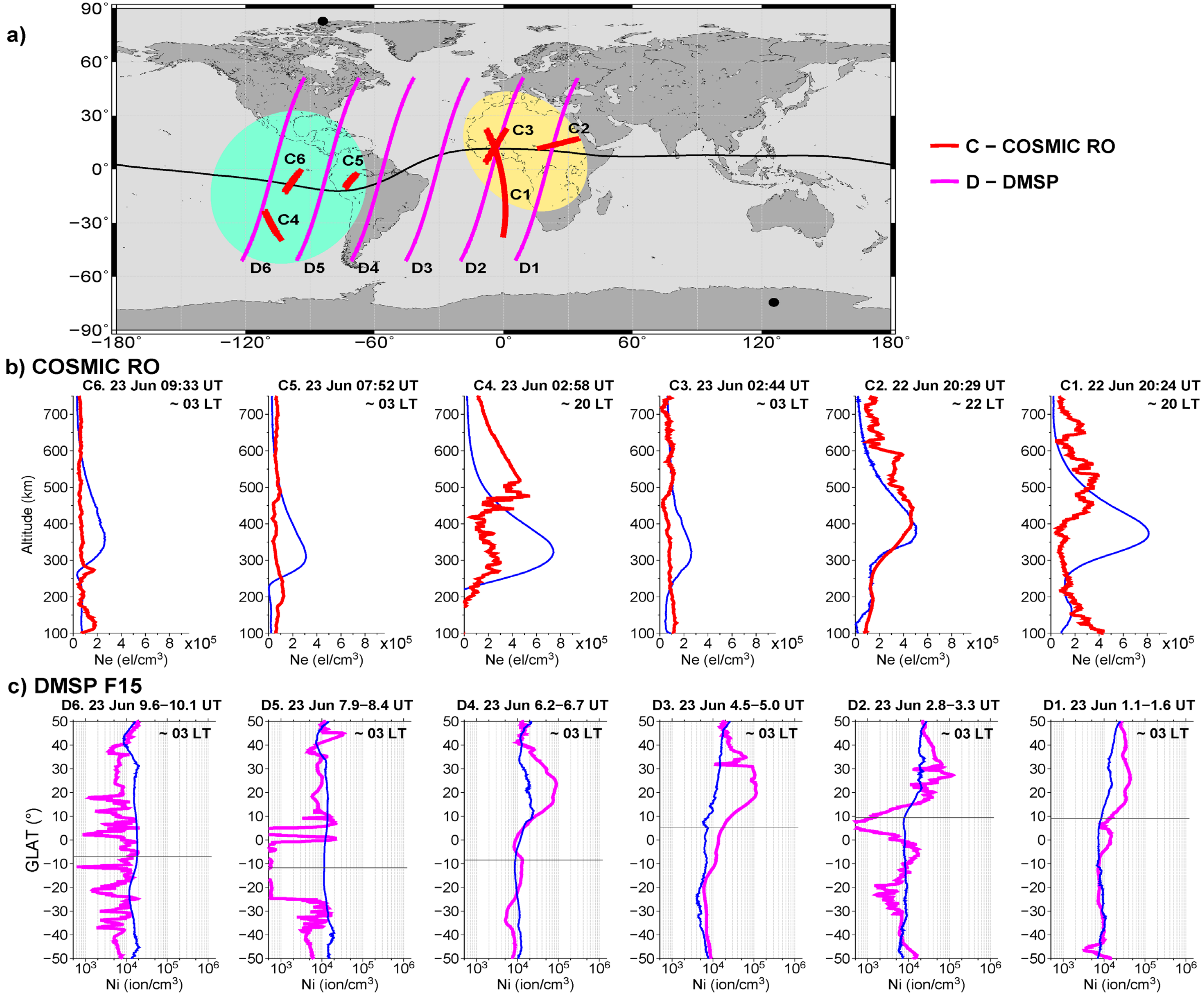
23/06/2015 0000 UT





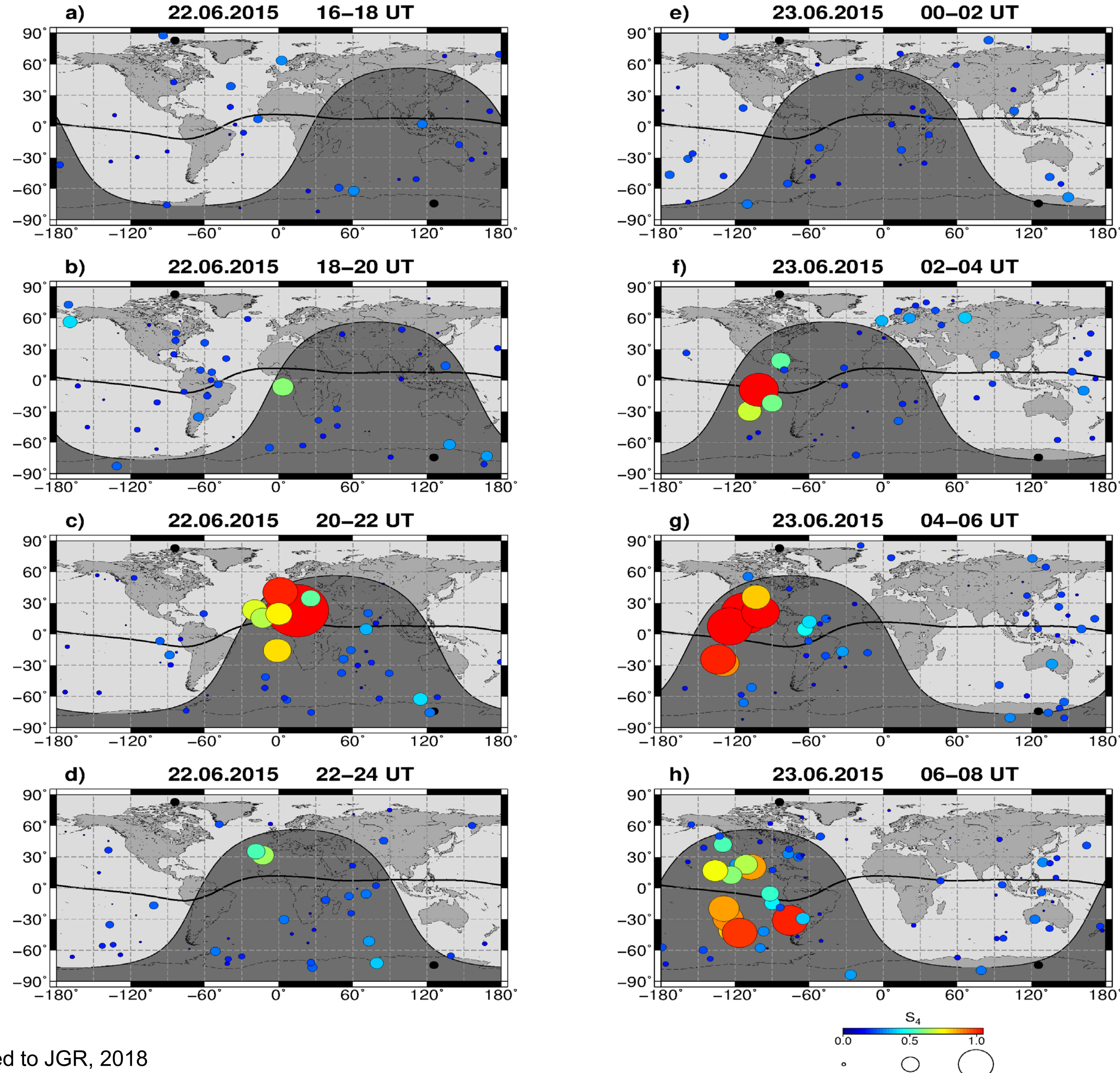
Cherniak et al, submitted to JGR, 2018

The June 2015 geomagnetic storm
Plasma bubbles on midlatitudes



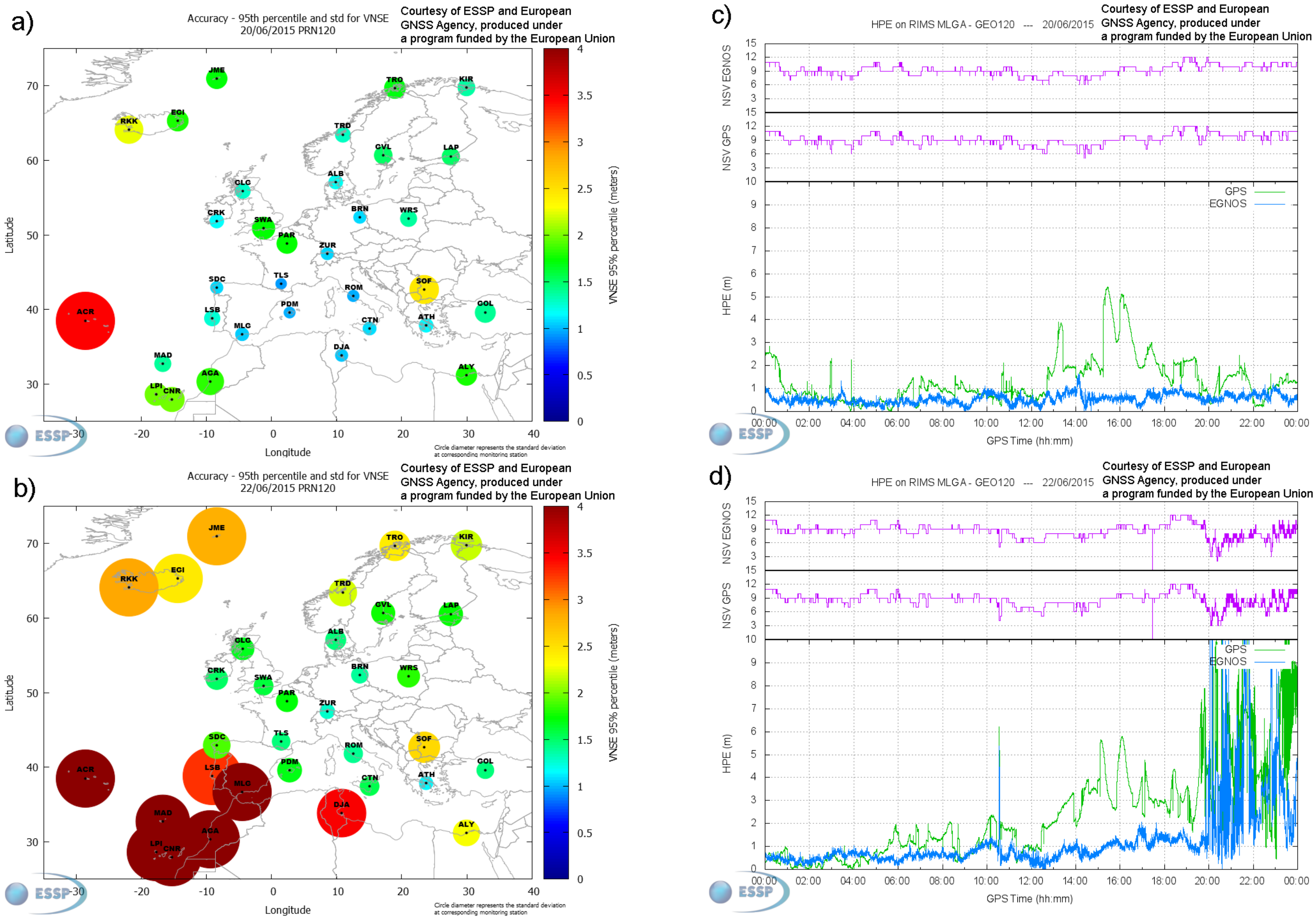
Cherniak et al, submitted to JGR, 2018

The June 2015 geomagnetic storm. Plasma bubbles on midlatitudes. COSMIC S4 index



Cherniak et al, submitted to JGR, 2018

The June 2015 geomagnetic storm. Plasma bubbles on midlatitudes. Impact on navigation performance



EGNOS, the European Geostationary Navigation Overlay Service. . It augments the satellite navigation systems and makes it suitable for safety critical applications such as flying aircraft or navigating ships through narrow channels.

Summary

Moderate and strong geomagnetic storms can drive formation of different types of ionospheric plasma irregularities. Typically developed on high latitudes with their further extension to midlatitudes but in same cases intense ionosphere plasma irregularities expanded from equatorial towards middle latitudes

Combination of ground based GNSS observations and space-based ionospheric measurements effectively contribute to tasks related with ionospheric plasma irregularities specification and Space Weather investigations :

- Day-today ionosphere irregularities variability and climatology
- Ionosphere plasma irregularities of auroral origin at high and mid midlatitudes
- Storm-induced topside plasma density enhancements and gradients
- Storm-induced midlatitude and equatorial irregularities and differences from climatology
- Analysis of ionospheric plasma irregularities impact on GNSS performance

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We acknowledge the European Space Agency (ESA) for providing the Swarm data (http://www.earth.esa.int/swarm)

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The AE and Kp indices are provided by the World Data Center for Geomagnetism, Kyoto University.

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Thank you for your attention!